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Stable isotope (δ^{18}O, δ^{13}C) records across the Cretaceous/Tertiary boundary at Geulhemmerberg, southern Netherlands

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Abstract

The stable isotopic (δ^{18}O, δ^{13}C) records for bulk samples and well-preserved, monospecific, benthic foraminiferal samples show no or only small variations across the Cretaceous/Tertiary (K/T) boundary at Geulhemmerberg, southern Netherlands. The site represents an inner shelf environment, where calcarenites and clay layers formed. Comparisons with previously established isotopic records from Danish K/T boundary sections, where significant isotopic changes (2–3 °C cooling and 1.5‰ negative δ^{13}C shift) occur in the basalmost P0 Zone, indicate a small hiatus at the base of the Danian at Geulhemmerberg. This is consistent with other data, such as absence of a strong Ir anomaly and shocked quartz.

The oxygen-isotopic values of planktonic, mid-depth-dwelling *Heterohelix globulosa* foraminifera, recovered from two early Danian Geulhemmerberg clay layers, are similar to, or more positive than the benthic values from the same layers. The origin of these apparently anomalous water-column δ^{18}O gradients is enigmatic. The inverted gradient may reflect sporadic development of an unusual water-mass stratification, such as the occurrence of an upper water mass with a slightly lower (1–2‰) salinity and with a few degrees lower temperature than bottom water. Alternatively, it may reflect different provenance areas of the planktonic and benthic foraminifera during turbulent conditions, while storm and back-wash deposits formed.

Overall, the whole-rock and benthic oxygen-isotopic records across the Geulhemmerberg section indicate fully marine (> 33‰) conditions throughout.

Introduction

Numerous studies have been performed of the stable isotopic (δ^{18}O, δ^{13}C) changes across the Cretaceous/Tertiary (K/T) boundary (see Corfield 1994, for a review). Despite many complications such as, in some cases, diagenetic signals and the use of poorly specified calcite material for isotopic analyses, some important results have emerged. A globally recognized negative shift in surface-water δ^{13}C at the boundary has been attributed to decreasing surface-water photosynthetic productivity, possibly associated with increased chemotrophic microbial respiration (Hsü and McKenzie 1990). Another important finding, by oxygen-isotope measurements, is a small cooling (≈ 3 °C) of the upper water mass as registered in shallow-depth benthic foraminifera and in 'survivor' planktonic foraminifera tests (Keller and Lindinger 1989; Schmitz et al. 1992; Keller et al. 1993). This cooling occurs in connection with the iridium-producing impact-event (Alvarez et al. 1980) and may be related to ejecta-dust in the atmosphere. A possibly more complex explanation, however, is indicated by the fact that a cooling trend already begins 1 to 3 m down in the Maastrichtian (Schmitz et al. 1992).

Here we present stable isotopic results for foraminiferal and bulk calcite samples across the K/T boundary at Geulhemmerberg in the southern Netherlands. The results are compared to the detailed isotopic records across the K/T boundary at Stevns Klint and Nye Kløv in Denmark (Schmitz et al. 1992; Keller et al. 1993). The two Danish sites together represent an expanded and probably complete K/T boundary section. The nearness of the Danish sites to Geulhemmerberg, and the fact that sediment formation at the three sites occurred in similar shelf environments, suggest potential for high-resolution isotopic correlations.

Material and methods

The study material includes fractions of the 24 samples used also by other researchers in the present multiparameter study of the Geulhemmerberg section (for information on site and sampling, see Brinkhuis and Smit, this issue). About half of the samples represent the calcarenites that dominate the section, and the other half clay layers that occur throughout the earliest Tertiary interval. Isotopic analyses were performed on well-preserved foraminiferal tests from the clay layers and from one of the calcarenite samples. In addition, all samples were analysed for whole-rock isotopic composition.

Monospecific assemblages of *Cibicidoides succedens* and *Cibicides bosqueti* were picked from sieving residues (63–250 μm) recovered at the Utrecht University. About 8 to 15 apparently well-preserved benthic specimens were used for each analysis. From some of the clay layers it was also possible to recover abundant specimens of planktonic *Heterohelix globulosa*. These also appeared well-preserved and only individuals without infillings were used. Although many individuals were quite large, about 40 to 60 specimens were required in order to achieve a weight of 40 to 50 μg, i.e. the amount of calcite preferred for the foraminiferal isotopic analyses.

For the whole-rock isotopic analyses about 2 to 3 g of each sample were ground and homogenized in an agate mortar, after which aliquots of about 500 μg were separated for analysis. The calcarenites contain no or only little nannofossil calcite, which makes them unsuitable for whole-rock isotopic paleoenvironmental reconstructions. Variations in the isotopic composition between different calcarenite samples may reflect changes in the proportions of different kinds of shell material, variations in carbonate mineralogy, as well as changes in water-mass temperature and chemistry. Generally, it is also very difficult to determine the possible influence of diagenesis on whole-rock isotopic compositions. Microscopical examination of the Geulhemmerberg calcarenites showed that they contain abundant diagenetic calcite. Small pieces of diagenetic calcite were recovered from one sample (G1A) and analysed separately.

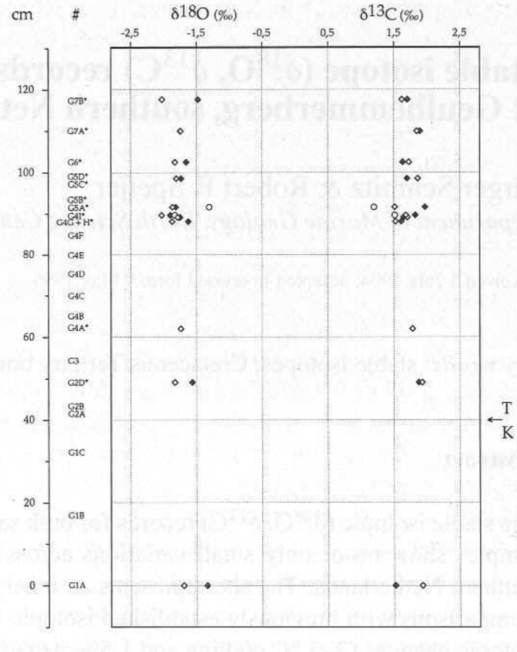

Figure 1. Stable isotopic composition of monospecific foraminiferal samples across the Geulhemmerberg K/T boundary. For sample positions see Brinkhuis and Smit, this issue. ◇ = *C. succedens*; ◆ = *C. bosqueti*; ○ = *H. globulosa*. # = sample numbers (asterisks denote clay layers).

All isotopic analyses were performed with a VG Prism Series II mass spectrometer at the Department of Marine Geology (Göteborg University). Calibration was made against NBS-19. Replicate analyses of this standard gave a standard deviation (2σ) of $\pm$ 0.01 for δ^{13}C and $\pm$ 0.06 for δ^{18}O. All results have been normalized versus the PDB standard using the δ notation.

Isotopic results

Foraminifera

The results for the monospecific foraminiferal samples are displayed in Figure 1. Both *Cibicidoides succedens* and *Cibicides bosqueti* show stable trends for carbon as well as oxygen isotopes throughout the studied interval. From the base to the top of the section, all carbon-isotope values lie between 1.5 and 2‰. In most of the samples the two species of benthic foraminifera give almost identical δ^{13}C values. Only two samples, G1A and G5A, show a significant isotopic divergence. The respective benthic oxygen-isotopic records are also very stable. Both δ^{18}O records could be best characterized by straight lines. There appears to be a small species offset, with *C. succedens* being generally slightly more negative than *C. bosqueti*. The average $\delta^{18}O$ value for *C. succedens* is – 1.8‰ (S.D. = 0.11‰) whereas *C. bosqueti* shows an average of – 1.66‰ (S.D. = 0.17‰). The consistency in the pattern indicates that *C. succedens* and *C. bosqueti* fractionate oxygen isotopes slightly differently or that they formed their tests at different seasons. Benthic foraminifera do not generally precipitate calcite in isotopic equilibrium with dissolved HCO_3^-. Instead, different species show different degrees of isotopic fractionation compared to equilibrium precipitation. These deviations are explained in terms of so called 'vital effects' (Grossman 1987). Disequilibrium fractionation, however, is relatively constant through time for each species, and as long as monospecific assemblages are compared, accurate determinations of relative changes in the isotopic composition of dissolved HCO_3^- and water-mass temperature can be made. Generally, diagenetic isotopic reequilibration or calcite infillings smooth out intraspecific isotopic differences (Barrera et al. 1987). The consistent occurrence of a small isotopic offset between the two benthic species throughout the Geulhemmerberg section represents supporting evidence for an excellent state of preservation of the original isotopic signals in the foraminifera.

The analyses of *Heterohelix globulosa* from two of the early Danian clay layers give interesting results. This planktonic foraminifer appears to have survived for some time into the early Danian after the impact of the giant extraterrestrial body at the K/T boundary (Keller et al. 1993). It belongs to the group of small foraminifera (heterohelicids, guembelitriids, hedbergellids, globigerinelloids) that generally occupied the upper 100–200 m of the water column in the Cretaceous ocean. Isotopic depth ranking indicates that among these groups, *Guembelitria* lived closest to the water surface (Kroon and Nederbragt 1990), whereas *Heterohelix* lived slightly deeper (Stott and Kennett 1989; Barrera and Keller 1990), followed by hedbergellids and globigerinelloids. At shallow-water sites such as at Geulhemmerberg, where the water depth may have been about 20 to 40 m (Roep and Smit, this issue), *Heterohelix* may have lived at mid-depths or relatively near the sea floor. This is consistent with the results for one of the two *Heterohelix* assemblages (G4I) analysed, which shows carbon- and oxygen-isotopic values identical to those of the benthic foraminifera. The second *Heterohelix* assemblage (G5A) shows slightly lighter carbon-isotopic values

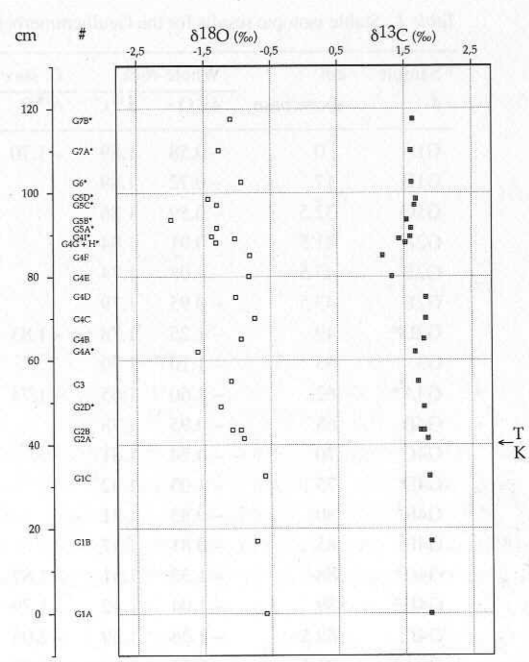

Figure 2. Stable isotopic composition of Geulhemmerberg whole-rock samples. # = sample numbers (asterisks denote clay layers).

and heavier (colder) oxygen-isotopic values than the benthics. This may imply an inverted temperature gradient or reworking of the two types of foraminifera from different areas (see below).

Bulk samples and diagenetic calcite

The whole-rock analytical results are displayed in Figure 2. The $\delta^{13}C$ record is relatively stable; however, there is a small gradual shift from values around 1.9‰ at the base to 1.6‰ at the top of the section. Two of the calcarenites (G4E and G4F) give low values around 1.3‰. There is no systematic difference between the carbon-isotopic compositon of the clay layers and the calcarenites. The bulk-sample oxygen-isotopic record shows larger variations. The calcarenites in the Cretaceous give $\delta^{18}C$ values around – 0.6‰, and in the interval just above the K/T boundary the values fall to – 0.9 to – 1.25‰. There is generally a difference in $\delta^{18}O$ between the clays and the calcarenites, with the clay layers being more negative than the calcarenites. The analysed fragments of diagenetic calcite from the G1A calcarenitic level give a substantially more positive $\delta^{18}O$ value (– 0.55‰) than the benthic foraminifera from the same level (– 1.34 and – 1.70‰; Table 1). The diagenetic crystals show almost the same oxygen-

Table 1. Stable isotopic results for the Geulhemmerberg section. For sample positions see Brinkhuis and Smit, this issue.

Sample	cm	Whole-rock		*C. succedens*		*C. bosqueti*		*H. globulosa*		Diagen. calcite	
#	above base	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$
G1A	0	− 0.58	1.89	− 1.70	1.93	− 1.34	1.52			− 0.55	1.95
G1B	17	− 0.72	1.89								
G1C	32.5	− 0.59	1.86								
G2A	41.5	− 0.91	1.84								
G2B	43.5	− 1.08	1.74								
G2B	43.5	− 0.95	1.79								
G2D*	49	− 1.25	1.78	− 1.83	1.93	− 1.57	1.88				
G3	55	− 1.10	1.70								
G4A*	62	− 1.60	1.65	− 1.74	1.78						
G4B	65	− 0.95	1.78								
G4C	70	− 0.74	1.81								
G4D	75	− 1.03	1.82								
G4E	80	− 0.83	1.31								
G4F	85	− 0.81	1.17								
G4G*	88	− 1.32	1.51	− 1.87	1.53	− 1.63	1.61				
G4H*	89	− 1.04	1.42	− 1.79	1.71	− 1.75	1.65				
G4I*	89.5	− 1.38	1.59	− 2.03	1.68	− 1.90	1.83	− 1.83	1.52		
G5A*	91.5	− 1.31	1.60	− 1.87	1.52	− 1.82	1.97	− 1.31	1.20		
G5B*	93.5	− 1.99	1.53								
G5C*	97	− 1.31	1.65								
G5D*	98.5	− 1.44	1.67	− 1.81	1.86	− 1.74	1.70				
G6*	102.5	− 0.94	1.61	− 1.83	1.73	− 1.66	1.64				
G7A*	110	− 1.28	1.60	− 1.74	1.85	− 1.75	1.89				
G7B*	117.5	− 1.10	1.62	− 2.03	1.62	− 1.48	1.70				

* = clay samples.

isotopic composition as the whole-rock sample. The diagenetic calcite may to a large extent represent biogenic calcite that has recrystallized post-depositionally, possibly at lower temperatures than when the original biogenic calcite formed. This is consistent with the $\delta^{13}C$ values, which are similar in the diagenetic calcite, the whole-rock as well as the benthic foraminifera. The similarity in $\delta^{18}O$ between the whole-rock and the diagenetic calcite at the G1A level indicates that recrystallized calcite represents an important fraction of the calcarenitic samples. The generally more negative $\delta^{18}O$ values of the clays compared to the calcarenites may be related both to a relatively lower amount of recrystallized calcite and to an originally higher content of nannofossil calcite. The calcareous nannoplankton thrived in warm water closer to the surface and hence registered more negative $\delta^{18}O$ values than the benthic organisms, whose shells are abundant in the calcarenites. At a shallow-water site such as Geulhemmerberg, the vertical $\delta^{13}C$ gradient in the water column in the earliest Tertiary may have been poorly developed, if not reversed, compared with normal conditions (Hsü and McKenzie 1990), which would explain why there is no difference in $\delta^{13}C$ between the clays and the calcarenites.

Comparisons with Denmark

For comparison we have plotted data for the K/T boundary at Nye Kløv and Stevns Klint in Figures 3 and 4, respectively (Schmitz et al. 1992; Keller et al. 1993). These sections belong to the most complete early Danian sections known. At Nye Kløv, at the very base of the Danian, however, there are a conglomerate and a small hiatus below a moderately Ir-rich marl layer. The boundary section from the Cretaceous to the Tertiary is better developed at Stevns Klint, where Maastrichtian chalk grades into a basal Danian spherule-rich red clay overlain by strongly Ir-enriched black clay (Schmitz 1988; Schmitz et al. 1992). With respect to completeness, the two sections together represent a next to ideal

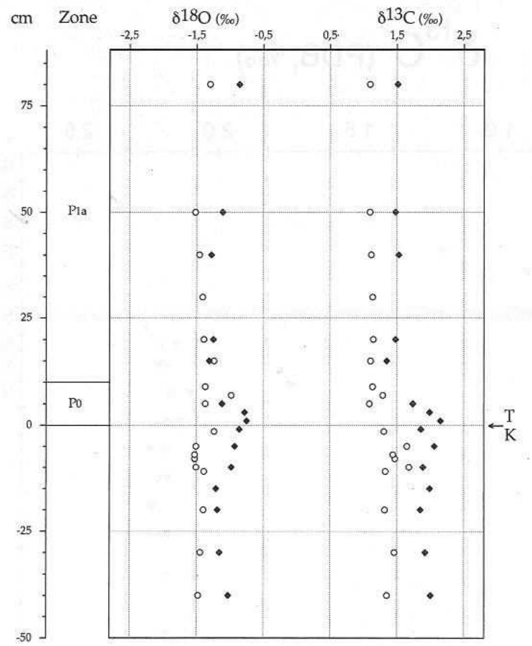

Figure 3. Stable isotopic composition of monospecific foraminiferal assemblages across the Nye Kløv K/T boundary (from Keller et al., 1993). ◆ = *C. succedens*; ○ = *H. globulosa*.

K/T contact. Foraminifera in the Danish sections are very well-preserved and useful for isotopic reconstructions.

Comparing the isotopic records for *C. succedens* between Denmark and Geulhemmerberg, indicates a hiatus in the Geulhemmerberg section at the base of the Danian. At Stevns Klint, a 0.5 to 0.6‰ (≈ 2–3 °C) cooling is registered in *C. succedens* in the lowermost centimetres of the Tertiary (basal Zone P0; Figure 4). At Nye Kløv the cooling appears to begin already 10 cm below the base of the K/T boundary marl, and reaches a peak in the 5-cm interval above this base (Figure 3). Already in the upper part of Zone P0 there is a return to lower δ^{18}O values. At Geulhemmerberg, on the other hand, in the lowermost Tertiary sample with useful foraminifera, G2D, *C. succedens* shows the same δ^{18}O value as in the rest of the section. No cooling is registered in the benthic foraminifera in any part of the Geulhemmerberg section. The whole-rock samples in the basal 10 cm of the Tertiary neither show any indication of cooling. A hiatus in the lowermost Danian at Geulhemmerberg is also supported by the absence of a strong Ir anomaly and shocked quartz. At Stevns Klint these features coincide with the isotopic anomalies.

In the Nye Kløv section some anomalous oxygen-isotopic values are registered for the planktonic *H. globulosa* in the upper P0 and the lower P1a Zone. In some of the samples from this interval, the *Heterohelix* δ^{18}O values are more positive or similar to values for the benthics. In the rest of the Nye Kløv section (Figure 3; Keller et al. 1993) and also in the upper Maastrichtian at Stevns Klint (Schmitz et al. 1992), *Heterohelix-Cibicidoides* oxygen-isotopic gradients always indicate a normal mid-depth-to-bottom temperature decrease. Because of the very shallow conditions at Geulhemmerberg, the normal situation in the Cretaceous at this site may have been that mid-depth-thriving *Heterohelix* registered similar isotopic temperatures as the benthics, as reflected in one (G4I) of the two analysed *Heterohelix* samples. However the reversed δ^{18}O gradient in the other *Heterohelix* sample (G5A) cannot be explained in this fashion. It may reflect sporadically unusual conditions in the earliest Tertiary water column, or, alternatively, reworking of benthic and planktonic foraminifera from different areas. The latter alternative is plausible considering that the sediments at Geulhemmerberg represent storm and back-wash deposits (Roep and Smit, this issue). However, the fact that the same pattern with inverted or absent δ^{18}O gradients in the early Danian has now been recognized at two sites separated by about 600 km, indicates that it may not just be a local phenomenon. The reversed *Heterohelix-Cibicidoides* δ^{18}O gradient in sample G5A at Geulhemmerberg also supports correlation with late P0 to early P1a sediments at Nye Kløv, which is consistent with biostratigraphic correlations (Brinkhuis and Schiøler, this issue). A long-term reversed temperature gradient in the water column is physically impossible, at least if salinity is the same throughout the water column. A possibility would be that warm, more saline, bottom water periodically underlay cooler, slightly less saline water (see Railsback et al. 1989). The isotopic reversal is primarily due to a change in the *Heterohelix* and not the benthic δ^{18}O values. Therefore, influx of cooler, less saline waters in the upper part of the water column may explain the reversal. Because lower salinity leads to lower, i.e. more 'warm' oxygen-isotopic values, a part of the true temperature difference may be masked by the salinity reduction.

Another explanation of the apparent isotopic reversal could be that it is related to calcite precipitation at different seasons of the year (see e.g. Bouvier-Soumagnac and Duplessy 1985). If benthic foraminifera preferably precipitated their tests during

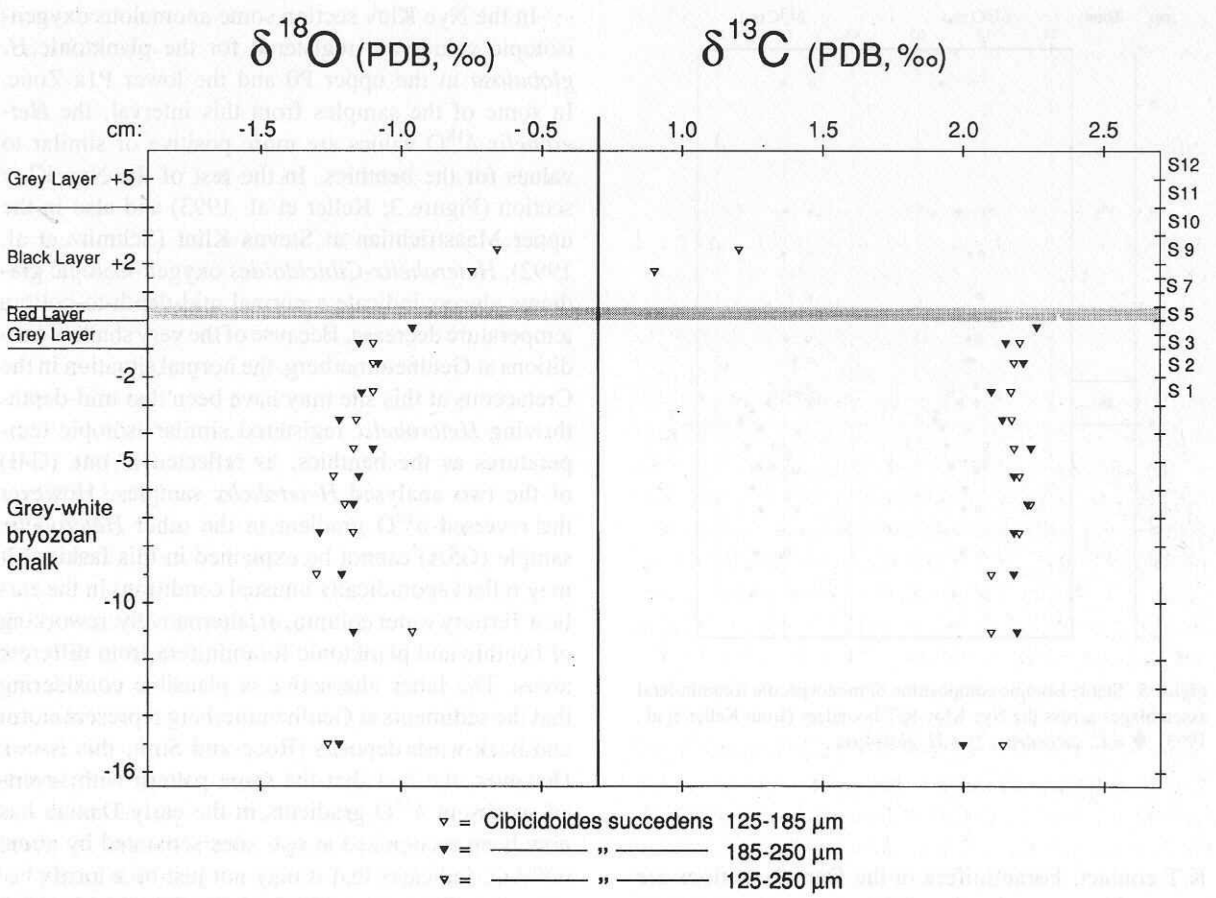

Figure 4. Stable isotopic composition of size-controlled monospecific samples of *C. succedens* across the Stevns Klint K/T boundary (from Schmitz et al., 1992). Division of K/T boundary clay according to Schmitz (1988).

the summer, and *Heterohelix* tests formed during a colder season, an inverted pattern would appear. Since the gradient is normal at all levels except in the late P0 and the early P1 interval, such an explanation, however, would require that any of the foraminifera changed their seasonal behaviour during a short period after the K/T boundary event. This is not very likely to have occurred, and one may instead argue that stronger seasonality changes evolved after the K/T boundary event. This together with temporal differences in calcite precipitation between the planktonics and the benthics, could have resulted in an apparent reversal of the isotopic gradient. More data, however, are obviously required to understand the unusual oxygen-isotopic gradient in the earliest Tertiary. Although the *Heterohelix* tests in the Geulhemmerberg section appear very well-preserved and lack infillings, influence from diagenetic processes cannot yet be entirely ruled out. The same applies for the *Heterohelix* tests from the earliest Danian at Nye Kløv. No detailed scanning electron microscope studies of these forams have yet been performed. Comparisons with Stevns Klint, where foraminifera tests usually also are excellently preserved, is not possible because of absence of planktonic tests in the boundary clay at this site.

The oxygen-isotopic values for *C. succedens* are about 0.5‰ more negative at Geulhemmerberg than at Nye Kløv, in accordance with shallower depths and higher bottom-water temperatures (≈ 2–3 °C) at Geulhemmerberg.

A problem with the Geulhemmerberg data is that we have only one value for the Cretaceous (sample G1A). It was not possible to separate foraminifera acceptable for isotopic use from the two other Cretaceous samples (G1B and G1C). The clay layers which contain well-preserved foraminifera are restricted to the early Tertiary part of the section.

Paleosalinity

The palynological data indicate that the Geulhemmerberg section represents an inner neritic, marginal marine environment, with nearby landmasses providing significant terrestrial input (Brinkhuis and Schiøler, this issue). In particular the abundance of Bryophyte spores in the earliest Danian, indicates a strong terrestrial influence, invoking the possibility of reduced salinities at some times. This possibility may be tested by means of oxygen isotopes, which are very sensitive to salinity variations and fresh-water influence. Even salinity reductions of only 2–3‰ compared with open marine conditions are readily recognizable in the oxygen isotopes. For example, deep-dwelling planktonic foraminifera in the semi-enclosed early Eocene North Sea show δ^{18}O values 1 to 4‰ lower than in contemporaneous fully marine environments (Schmitz et al. 1996). Assuming that the present-day North Atlantic δ^{18}O-salinity relation also applies in the Eocene, implies salinities between 28 and 32‰ in the upper water mass in the North Sea at this time. At Geulhemmerberg, in the K/T boundary interval, the oxygen-isotopic values for the benthics are stable and similar to values measured in other coeval marine environments, indicating fully marine salinities (> 33‰) throughout. The whole-rock clay samples from Geulhemmerberg neither show any unusually low δ^{18}O values, indicative of fresh-water influence. In the lower Eocene North Sea sediments, the whole-rock samples show particularly low δ^{18}O values (– 4 to – 5‰), because the nannofossils constituting the major fraction of the calcite, also registered the isotopic composition of the upper part of the water mass where the lowest salinities occurred (Schmitz et al. 1996). In near-coastal areas affected by intermittent fresh-water influx, the salinity-sensitive oxygen isotopes may fluctuate considerably (cf. Schmitz et al. 1996), a pattern not seen in the Geulhemmerberg section.

As discussed above, the anomalously positive *Heterohelix* data in sample G4I may reflect water masses that were cooler, but also less saline, than bottom water. If real, the salinity reduction compared with bottom waters probably was very small (1–2‰), otherwise the salinity effect would have overprinted the temperature effect, leading to more negative δ^{18}O values instead. If the upper water mass was a few degrees colder and slightly less saline than the bottom water, a normal density-stratification would be possible (see Railsback et al. 1989).

Environmental changes at the K/T boundary

The isotopic records at Geulhemmerberg show almost no changes across the K/T boundary. Compared with many isotopic records previously established over the K/T boundary worldwide, the Danish records show much less pronounced changes, in particular for δ^{13}C (Hsü et al. 1982; Perch-Nielsen et al. 1982; Zachos and Arthur 1986; Stott and Kennett 1989; Zachos et al. 1989; Barrera and Keller 1990; Corfield 1994). There may be several reasons why the northwestern European isotopic records appear more stable, one being the fact that most of the earlier published records, displaying pronounced δ^{13}C changes, have been measured on fine-fraction or bulk-sample calcite. These records are generally considered to reflect conditions in the upper part of the water column, based on the assumption that the bulk or fine-fraction calcite is dominated by nannoplankton calcite. It is generally very difficult to determine the effects of diagenesis or of changing vital isotopic fractionation related to floral and faunal shifts on whole-rock isotopic compositions. Therefore such data are less useful than data from well-preserved foraminifera tests, for which isotopic fractionation factors and depth origins are better understood.

The northwestern European isotopic records across the K/T boundary are based on generally very well-preserved monospecific planktonic and benthic foraminiferal assemblages in expanded sections. These are among the most reliable K/T boundary isotopic records so far established. Why are the isotopic changes absent or so small in these sections? Has the magnitude and extent of the surface-water δ^{13}C decline at the K/T boundary been overestimated in earlier studies? If a long-term productivity crisis with associated profound global δ^{13}C decline in the upper water mass did occur, it would have left some traces also in the δ^{13}C record of benthic foraminifera at shallow-water sites such as Geulhemmerberg and Denmark. At Stevns Klint a profound δ^{13}C shift ($\approx$ 1.5‰) is indeed registered in the benthic foraminifera in the lowermost centimetres of the Danian (Figure 4). The duration of this large δ^{13}C shift, however, is quite short, having been recorded only in the basal P0 Zone (Schmitz et al. 1992). At Nye Kløv there is a small ($\approx$ 0.5‰) negative δ^{13}C shift in both planktonics and benthics, starting at the K/T boundary and continuing for quite a long time (at least into Zone P1b) in the early Danian. At Geulhemmerberg hardly any $\delta^{13}C$ shift at all is recognizable at the K/T boundary.

Keller et al. (1993) propose that the comparatively small changes in the isotopic records at Nye Kløv reflect that there were only minor effects of the K/T boundary impact event in high latitudes. This arguing, however, is based on a comparison primarily with the low-latitude Brazos River section (Texas, U.S.A.), where major $\delta^{13}C$ and $\delta^{18}O$ changes have been measured in monospecific foraminiferal samples across the K/T boundary (Barrera and Keller 1990). Corfield (1994), however, proposes that the strong correlation between the carbon- and oxygen-isotopic trends in the Brazos River section may implicate strong diagenetic overprinting, an interpretation with which we agree. The evaluation of the Brazos River isotopic data must await more detailed studies of the preservation of the foraminifera in the section. Until more detailed high-quality low-latitude isotopic data have been produced, it is not possible to determine whether there is a major difference in environmental effects of the K/T boundary impact event between low and high latitudes.

Judging from the oxygen-isotopic patterns for the northwestern European sections, the temperature changes in connection with the K/T boundary event were very small. A cooling of 2–3 °C in benthic values in the Danish sections and a possible short-term reversal in the *Heterohelix-Cibicidoides* temperature gradient are the only recognizable climate effects in northwestern European shelf seas.

Strong effects on water-mass temperature and chemistry in connection with the K/T boundary event may have had a very short duration in northwestern Europe, and therefore may only be registered in the most expanded and complete sections across the boundary. This is consistent with the most dramatic isotopic shifts having been measured over a few centimetres in the basal K/T boundary clay at Stevns Klint (Schmitz et al. 1992). The most intense effects may have occurred during an even briefer period, when foraminiferal tests formed only rarely because of strong environmental stress. The likelihood to recover isotopic signals reflecting such an event is small.

A possibility that has to be considered for the Geulhemmerberg results, is that the foraminifera tests in the Danian are reworked from Cretaceous deposits. This could explain the apparently unusual stability of the isotopic trends across the K/T boundary at this site. The occurrence of calcarenites throughout the major part of the section is consistent with high water energies that may be associated with reworking processes. However, the generally well-preserved state of the foraminifera tests (including also well-preserved fragile *Heterohelix* tests) and the presence of early Tertiary dinoflagellates in the clay intervals, speak against the reworking hypothesis, at least for the clays.

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